

Life cycle costs optimization of residential buildings. Part I: a case study of external walls

Nadezhda Doseva¹, Daniela Chakyrova¹

1 – Technical University of Varna, Department of Heat Technology, 9010, 1 Studentska Street, Varna, Bulgaria.

Corresponding author contact: nadezhda.doseva@abv.bg

Abstract. *This paper considers the questions of techno-economic optimization in order to determine the thermal transmittance coefficient of the external walls of an existing residential building. The optimization procedure is conducted for the climatic and economic conditions in Bulgaria and taking into account the existing legal framework. The minimum of the building life cycle costs is determined by using genetic algorithm.*

Keywords: genetic algorithm, life cycle costs, optimization, optimal thermal transmittance coefficient

1 Introduction

The building sector can be identified as one of the world's major energy consumers. More specifically, for the period 1971-2004, CO₂ emissions, including through the use of electricity in buildings, is estimated to have grown at a rate of 1.7% per year for residential buildings. The majority of emissions were generated from residential buildings in North America, Western Europe, and the Eastern Europe, Caucasus and Central Asia regions. According to data from United Nations Environment Programme, (2009), the total emissions from residential buildings in the countries of North and South America, the east and south of Asia and North-East Africa will surpass these regions by 2030 (United Nations Environment Programme, 2009).

In this regard, the task associated with rational use of energy in residential buildings is not only of national but also of global importance. Due to the well-known fact that there is a close connection between the energy consumption of the building and the thermal characteristics of its envelope, it is necessary to seek for technical and economical optimal solutions both for the renovation of the existing building sector and in the case of new buildings.

In order to meet the challenges of the building sector, the European Union published a Directive on the energy performance of buildings (Directive 2002/91 / EC) in 2002, which was subsequently developed by Directive 2010/31 / EU. The revised Directive places the focus on improving energy efficiency by introducing minimum requirements for buildings and building components, and sets as a political objective the construction of Nearly Zero Energy Buildings (nZEB) (European Parliament, 2010). In addition to the nZEB policy, in 2012, a methodological framework is also introduced to achieve optimal costs over the life-cycle of buildings (European Parliament, 2012).

Along with the European legal framework, there are a researches focused on identifying the lifecycle cost optimization of the new buildings, as well as existing buildings and building constructions. Becchio et al. (2015) determined the various techno-economical optimal solutions for building constructions and design solutions for the building technical systems in nZEB located in Italy. In another study (Bojic, 2014), thermal insulation layer is optimized applying Hooke-Jeeves direct search method. The object is a small residential house in Serbia. Moreover, Dombayci et al. (2017) determined the optimum insulation thickness of an external wall using thermoeconomic method based on exergy. In this paper, the minimum thickness of thermal insulation layer is calculated taking into account the climate data for four different regions in Turkey.

It is important to note that the results obtained in reference literature cannot be directly applied to the buildings sited in Bulgaria due to the fact the economic optimum strongly depends on the localization of the object.

The aim of the present study is to determine the optimal values of the thermal transmittance coefficient. In this regard, the optimum insulation thickness of the external wall was determined using thermoeconomic method taking into account the effect of the inflation and interest rate. This method is

called Life Cycle Cost Analysis (LCA). The determination of the optimum insulation thickness of the external wall of the residential building is conducted for the selected cities in four different climate regions in Bulgaria.

2 Method

2.1 Optimization problem. Independent variables and objective function

In this paper, in order to obtain the optimal energy efficiency levels, the following combination of design variables was investigated: the thermal transmittance of external walls and life cycle costs of the measures for increasing energy efficiency level in the building.

In this optimization problem the thermal transmittance of the external walls of the building, x_i [W/(m²K)], are taken as decision variables and the following values are searched for: x_1 - thermal transmittance of the northern exterior walls of the building; x_2 - for exterior walls with south orientation; x_3 - for exterior walls with eastern orientation; x_4 - for exterior walls with western orientation.

In order to modify the thermal transmittance coefficient, x_i , and to search for its optimal value, $U_{opt,i}$, it is accepted to vary the thickness of the thermal insulation layer, y_i . Its value will change to a defined allowable space, Γ_x :

$$0 \leq y_i[m] \leq 0.2, i = 1, 2, \dots, 4, \text{ or } y \in \Gamma_x \quad (1)$$

In current mathematical model, extruded polystyrene was considered as a thermal insulation layer. It is the most common used thermal insulation material used in Bulgaria.

In addition to the independent parameters, in the vector of input variables are also included:

- *Vector of constructive parameters:* $d = (A_k, A_f, V, A_{sol}) \in \Gamma_d$,

where: A_k [m²]- the area of the k -th building element (walls, roof, floor, windows and etc.);

A_f [m²]- total area of the heated / cooled spaces in the building;

V [m³] - volume of the heated / cooled spaces in the building;

A_{sol} [m²]- effective area of transparent and opaque enclosures.

- *Vector of constant parameters:* $x^c = (U_k, R_{t,w}, \Phi_r, F_{sh,ob}, Q_{int}) \in \Gamma_c$,

where: U_k [W/(m²K)]- the thermal transmittance coefficient of the k -th element of the building (roof, floor, windows);

$R_{t,w}$ [m²K/W] - heat resistance of non-insulated external walls;

Φ_r [W] - the heat flux resulting from the emission from k -th element to the sky;

$F_{sh,ob}$ - shading factor of the receiving solar energy surface.

In this article, the building is considered as a constructed object. Therefore, d is constant and refer to x^c ($\Gamma_d \subset \Gamma_c$).

In general, the optimization problem is defined as follows: looking for a minimum of the total monetary cost of the building and the building elements for a certain period of time, τ , $C_g(\tau)$ expressed in the following objective function:

$$f(x) = C_g(\tau)(x_1, x_2, \dots, x_4) \quad (2)$$

in a space defined by $x \in \Gamma_x$.

2.2 Mathematical model

In the present study, the developed mathematical model of the reference test-cell buildings was divided in two parts. Firstly, the energy needs of the building (on an annual basis) were modeled. Secondly, the global cost over the calculation period τ were estimated.

Energy assessment of the reference residential building

The energy assessment was performed by means of the methodological framework of the Regulation №7 for energy efficiency in buildings (Ministry of Regional Development and Public Works,

2017). It was simulated the energy behavior of the reference building and it was evaluated its annual heating and cooling needs, Q .

Global cost over the calculation period τ

In order to evaluate the cost-optimal energy efficiency levels of the reference building, the methodological framework of the European Regulation 244/2012/EU was carried out. According to European Regulation 244/2012/EU, the global cost of a measure or group of measures, j , for improving the energy efficiency level of the building from a financial point of view is determined as follows (European Parliament, 2012):

$$C_g(\tau) = C_I + \sum_j \left[\sum_{i=1}^{\tau} (C_{a,i}(j) \cdot R_d(i)) - V_{f,\tau}(j) \right] \quad (3)$$

where: τ - a calculation period, which in the present study identifies the economic life of the building. It is assumed to be $\tau = 30$ year (European Parliament, 2012);

$V_{f,\tau}(j)$ - residual value of measure or set of measures j at the end of the calculation period (discounted to the starting year τ_0), in BGN. In this study is assumed that $V_{f,\tau}(j) = 0$ at the end of the economic life of the building;

$R_d(i)$ - discount factor for year i based on discount rate r . It can be written as (European Parliament, 2012):

$$R_d(i) = \left(\frac{1}{1 + r/100} \right)^i, \quad (4)$$

where: r is the real discount rate.

According to the guidance of the European Regulation 244/2012/EU (European Parliament, 2012), it is assumed that the real discount rate is equal to $r = 6$.

C_I - initial investment costs for measure or set of measures j , BGN;

$C_{a,i}(j)$ - annual cost during year i for measure or set of measures j , BGN.

In this paper, initial investment costs, C_I , are considered as a sum of the cost of materials, labor, equipment, and design fees incurred for thermal insulation layer of the building's external walls. In addition, the initial investment costs of heating and cooling system for the building, $C_{I,HEAT}$, are considered as dependent variable. Therefore, initial investment costs are:

$$C_I = C_{I,ins} + C_{I,HEAT} + C_{I,P}, \text{ [BGN]}, \quad (5)$$

where: $C_{I,ins}$, [BGN] - initial investment costs for the thermal insulation layer. It is defined as follows:

$$C_{I,ins} = \sum_{n=1}^i C_{ins} \cdot y_i \cdot A_i + C_{mount} \cdot \sum_{n=1}^i A_i + a_1, \text{ [BGN]}. \quad (6)$$

The term in equation (6) are: C_{ins} - the purchasing cost of the thermal insulation material (in BGN / m^3); y_i - thickness of the insulation layer on the wall with i -th cardinal direction (m); C_{mount} - mounting costs of insulation layer (in BGN/ m^2); A_i - area of external walls with the i -th cardinal direction (m^2); a_1 - purchase and installation cost of the additional materials (dowels, mesh, plaster, etc.) [BGN].

$C_{I,HEAT}$, [BGN]- purchasing and mounting costs of the heating and cooling system of the building, taken as a sum of the mounting costs of the heat source (air to water heat pump), $C_{I,HP}$, of the fan coils, $C_{I,C}$, of the pipe network, $C_{I,pipe}$, and of the additional and auxiliary equipment, $C_{I,ax}$.

In the mathematical model of the reference building, the costs of purchasing and installing the heat source, $C_{I,HP}$, and fan coils, $C_{I,C}$, are also considered as dependent variables. They are defined as a function of the design heating, Φ_{HL} , and the cooling load $\Phi_{t,CL}$, of for a building entity or a building. The determination of design cooling and heating load was conducted by means of the methodological framework of the Regulation №15 for technical rules and norms for the design, construction and oper-

ation of the units and equipment for the generation, transmission and distribution of heat (Ministry of Regional Development and Public Works, 2016).

$C_{I,P}$, [BGN] - costs for design fees.

In the mathematical model of the reference building, maintenance costs during the i -th year are considered as the sum of the repair, recommissioning, replacement, and asset preservation costs of the heating and cooling system and the heat insulation layer of the external walls. Under current market prices, these costs can be defined as:

$$C_{I,P} = 1\% \cdot C_I, \text{ [BGN]} \quad (7)$$

The operating costs of heating and cooling system, $C_{H/C}$, include with the fuel costs incurred during the i -th year of the building's economic life. They are defined as a product of the annual energy demand of the building, and the electricity price as of 01.07.2018, $c_{el} = 0.21596 \text{ BGN} / \text{kWh}$ (Energo Pro, 2018):

$$C_{H/C} = c_{el} \cdot Q, \text{ [BGN]} \quad (8)$$

2.3 Optimization algorithm

In the present publication, the genetic algorithm (GA) has been chosen as an optimization technique. The genetic algorithm is a method for solving both constrained and unconstrained optimization problems. GA is based on natural selection, the process that drives biological evolution. This method is meta-heuristic optimization method – a part of stochastic search methods. GA build on traditional optimization techniques based on random search methods, and its characteristic feature is that GA does not handle a single solution but with a multitude of acceptable solutions of optimization problem - encoded vectors of the independent variables called population.

The numerical solution of the optimization problem is performed after setting the values for the turning parameters in genetic algorithm that are presented in Table 1.

Table 1. The turning parameters in genetic algorithm.

Parameter of GA	Value / Method
Population size, N_p	500
Maximum number of generations, i_{max}	200
Selection process	Wheel of roulette
Number of elite children at each population	2
Crossover fraction at each population, p_c	80%
Number of crossing points	two
Method of mutation	Adaptive mutation

The criteria for terminating the GA are the following:

- Maximum number of generations, i_{max} ;
- Stall generation: $i_{stall} = 150$;
- Function tolerance: $h_{min} = 1.10^{-6}$ - the algorithm stops when the average relative change in the fitness function value over stall generations is less than function tolerance.

The optimization is performed using genetic algorithm in MATLAB optimization environment, i.e. using Matlab Optimization toolbox. The following steps outline the optimization procedure in MATLAB environment:

- Fitness function (equation 2): it is enter in the form @optimumFvalue, where optimumFvalue.m is a file that calculates the objective function;
- Setting the length of the input vector: in this case, the length of the input vector is 4;
- In the constraints pane of the Matlab Optimization toolbox are specified the boundary conditions of the optimization problem (eq. 1) as real vectors.
- Setting the optimization options: in the option pane of the Matlab Optimization toolbox are entered the values of the turning parameters in genetic algorithm listed in Table 1.

The schematic diagram of the genetic algorithm used for solving the problem is shown in Fig. 1.

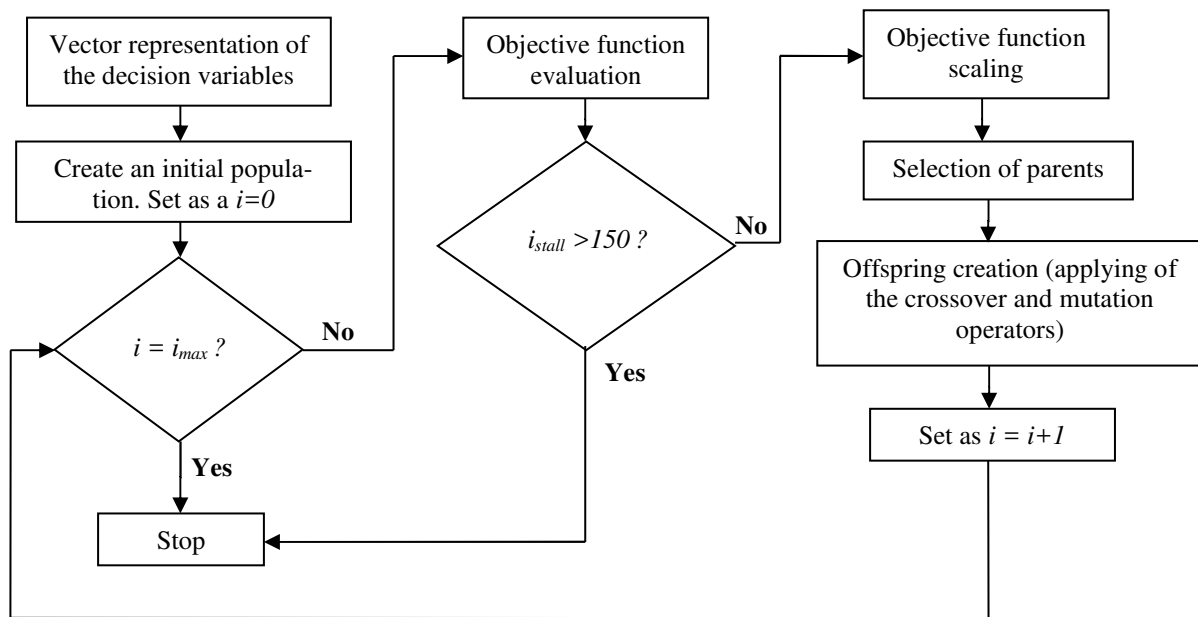


Fig. 1. Scheme for genetic algorithm used in the present work

3 Description of the considered residential building

The considered building is two-family dwellings with a total number of occupants - 8 people. It is assumed that it is average height buildings in city centers, i.e. the reference building is with heavy shielding. The heated and cooled volume of the building is $V = 510 \text{ m}^3$ and the area - $A_f = 179.2 \text{ m}^2$.

The total area of the glazed elements is $A_w = 36.15 \text{ m}^2$ and they are located on the north and south facades of the building. Part of the floor of the building (15 m^2) is above an unheated basement and the rest of the floor slab (74.6 m^2) is ground floor. The roof of the building is warm and with area $A_{\text{roof}} = 90 \text{ m}^2$. Area of the external walls of the building is 206.156 m^2 .

The thermal transmittances, U_k , for the ground floor, floor over an unheated basement, the roof, the thermal and optical characteristics of the glazed elements and the thermal resistance of the non-insulated external walls, $R_{t,w}$, are considered as constant variables in the mathematical model of the reference building. Description of the construction layers of the reference building elements are listed in Table 2.

Table 2. Construction layers of building envelope elements

External walls	Roof	Ground floor	Floor over an unheated basement	Windows
2cm lime, sand plaster (outside); y_i cm extruded polystyrene; 25cm brick masonry; 2cm lime, sand plaster (inside).	2.5cm ceramic tiles; 0.4cm bitumen; 12cm mineral wool; 0.3cm vapor barrier; 3cm oriented strand board; 12cm wooden ribs (beech).	14cm gravel; 12cm reinforced concrete; 4cm extruded polystyrene; 2.0cm cement screed; 0.7cm tile.	12cm reinforced concrete; 3cm extruded polystyrene; 2.0cm cement screed; 0.7cm tile.	Frame: PVC with $U_f = 2 \text{ W} / (\text{m}^2\text{K})$; Glass package with $U_g = 1.4 \text{ W} / (\text{m}^2\text{K})$: triple glazing 4/9/4/9/4mm and air filled; Low-emission coating
$R_{t,w} = 0.7275 \text{ m}^2\text{K/W}$	$U_r = 0.24 \text{ W} / (\text{m}^2\text{K})$	$U_{gf} = 0.35 \text{ W} / (\text{m}^2\text{K})$	$U_f = 0.39 \text{ W} / (\text{m}^2\text{K})$	$U_w = 1.62 \text{ W} / (\text{m}^2\text{K})$

The internal heat gain of people, appliances and lighting were defined to be $\Phi_{\text{int}} = 0.349 \text{ kW}$.

For the life cycle cost optimization process, four cities were selected, as representative of the different climate characteristics in Bulgaria: the city of Varna, which is located in climate zone №1; the city of Sozopol (climate zone № 5); the city of Nova Zagora and Sofia (climate zone № 6 and 7, respectively). Climate data, such as average monthly outdoor air temperature, average solar radiation,

start and end of the heating season and etc. are determined according to the data in the Regulation №7 for energy efficiency in buildings (Ministry of Regional Development and Public Works, 2017).

Heating and cooling system

The heating and cooling system of the reference building is based on modulating, “split-system” air-to-water heat pump. Air-to-water heat pumps are powered by electricity and therefore, electrical energy is considered as a fuel of the heating and cooling system. The system use liquid heat-transfer medium, i.e. the working fluid is water. The hydronic heating and cooling system use zoned fan coils. The distribution side of the system is a two-pipe direct return layout using a variable-speed, pressure-regulated circulator. Domestic hot water is heated by the heat pump. In case of any necessary temperature boost, an auxiliary electric heating element on the top of the water heating tank is provided.

4 Results and discussion

Table 3 presents the data obtained of the optimal thermal transmittance coefficients determined using the methodology of this paper. The results relate to the considered reference residential building and they are arranged according to the location of the buildings and the cardinal direction of the building elements.

Table 3. The optimal thermal transmittance coefficients of the external walls

Climatic zone	U _{opt, is} [W/m ² K]			
	North	South	East	West
№1 (Varna)	0.2285	0.2381	0.2467	0.2450
№ 5 (Sozopol)	0.2332	0.2432	0.2522	0.2504
№6 (Nova Zagora)	0.2373	0.2491	0.2564	0.2527
№ 7 (Sofia)	0.2128	0.2211	0.2285	0.2255

As Table 3 and 4 shows, there is a slight difference between results for U_{opt, i} as a function of the cardinal direction of the external walls - for all of the considered climate zone. Closer inspection of the data in table 3 and 4 shows that there is a slight decline in the results moving from the east (climatic zone №1 and №5) to the west Bulgaria (climatic zone №7). The decrease in U_{opt, i} is negligible, even if the location of the building is changed from south to north in the Black Sea areas of Bulgaria (climatic zones №5 and №1). Therefore, the results suggest that it is necessary to draw up an energy map of Bulgaria.

Table 4. The optimal thickness of the extruded polystyrene insulation and global cost over the calculation period

Climatic zone	Thickness of the thermal insulation layer, [m]				C _g (τ), [BGN]
	North	South	East	West	
№1 (Varna)	0.125	0.119	0.114	0.115	124906.60
№5 (Sozopol)	0.122	0.116	0.111	0.112	124250.62
№6 (Nova Zagora)	0.123	0.116	0.112	0.114	124427.96
№7 (Sofia)	0.136	0.13	0.125	0.127	128015.93

It is important to note, that the results showed in Table 3 and 4 are in agreement with those obtained by Loukaidou (2017): the optimal thermal transmittance coefficients of the external walls of a building sited in Saïttas (Cyprus) is U_{opt} = 0.28W/(m²K) (Loukaidou, 2017).

The results of the current study are also consistent with that of Dombayci et al. (2017) who found that the optimal insulation thickness for expanded polystyrene insulation is 0.107m. In this study, the cited value of the optimum insulation thickness of a typical external wall was calculated with climatic data for province Kars in Turkey.

This study also accords with our earlier observations (e.g. Doseva et al., 2017), which showed that the optimal insulation thickness for expanded polystyrene insulation is 0.108m. This difference can be explained by the specifics of the mathematical model in (Doseva et al., 2017): the optimization was conducted using the different climatic data (at climatic zone №9); natural gas and electricity was used as fuels; the economic parameters of the mathematical model had values typical of 2017.

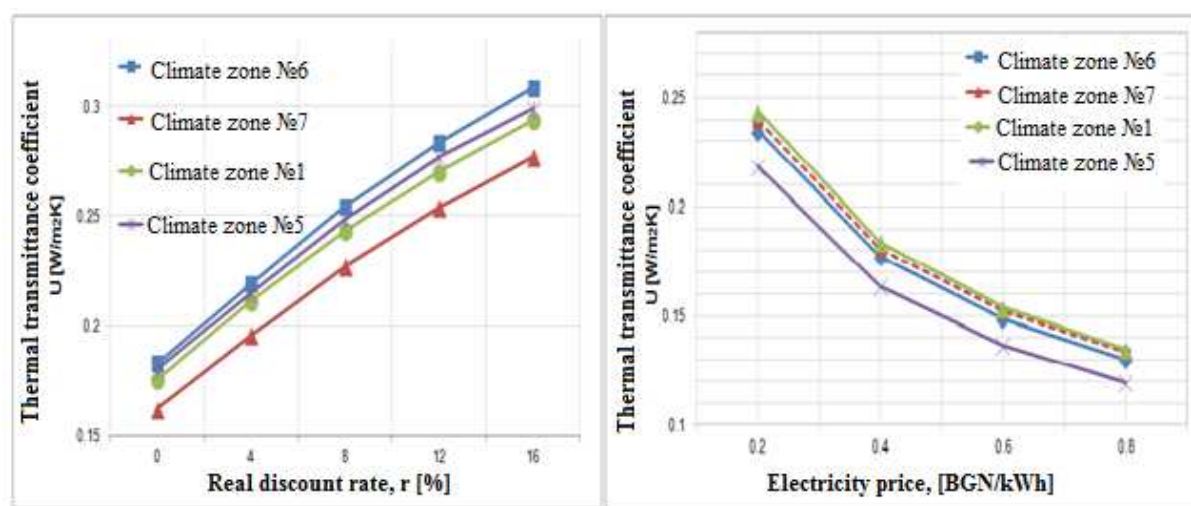


Fig. 2. The optimal thermal transmittance coefficients of the northern external walls, U , in relation to the real discount rate (left) and electricity price (right)

A sensitivity analysis of one of the independent variables of the optimization procedure (U_{opt} for the northern external walls) is shown in Figure 2. In Fig.2 there is a clear trend of decreasing the values of the optimal thermal transmittance coefficients of the northern external walls with increasing of the electricity price. In addition, it is possible to assume 2% rise of the market price of electricity. Therefore, at the fifteenth year of the economic life of the reference building, c_{el} will be 0.285 BGN/kWh and at the end of the period - 0.3835 BGN/kWh. In this case, as can be seen from the data in Figure 1, the U_{opt} of the northern walls of the reference building in climatic zone №7 is expected to decline steadily to 0.189 W/(m²K) and 0.169 W/(m²K), respectively.

On the other hand, if inflation rate, b , will growth continually and it reach a peak typical for 2008 ($b = 12.3\%$, i.e. $r = 8.65\%$), U_{opt} will rise to 0.232 W/(m²K) (for climatic zone №7) and around 0.25 W/(m²K) for the other considered climatic zones.

5 Conclusions

In this study, the optimum thermal transmittance coefficients for the external walls of a residential building was calculated using the life cycle cost analysis method and genetic algorithm for four different climatic zones in Bulgaria. The results of this investigation show that the impact of the energy performance of building envelope on the life cycle costs of the building is complex. Therefore, further modeling work will have to be conducted and it will consider the heat coefficients for the external walls, floor, roof and glazed elements as independent variables.

The findings of this study suggest that in general the cardinal direction of the external walls do not influence significantly on the U_{opt} values. However, this question is essential in case of glazed building elements and further work needs to be done to establish the optimal thermo-optical characteristics of the windows.

The results of this study indicate that the optimal thermal transmittance coefficients of external building components can be most fully and precisely determined by taking into account the heat storage capacity during the winter and summer periods of the non glazed building elements. Therefore, this investigation lays the groundwork for future research into the field of non steady state heat and mass transfer through the building envelope and HVAC system within the building.

Acknowledgements The authors would like to express their very appreciation to Professor Nikola Kaloyanov for his valuable and constructive suggestions, recommendations and support during the planning and development of this research work.

References

- Becchio C., Dabbene P., Fabrizio E., Monetti V., Filippi M. (2015). Cost optimality assessment of a single family house: Building and technical systems solutions for the nZEB target. *Journal of Energy and Buildings*, 90, 173-187. <https://doi.org/10.1016/j.enbuild.2014.12.050>
- Bojić M., Miletić M., Bojić L. (2014). Optimization of thermal insulation to achieve energy savings in low energy house (refurbishment), *Journal of Energy Conversion Management*, 84, 681-690. <https://doi.org/10.1016/j.enconman.2014.04.095>
- Dombayci, Ö., Atalay, Ö., Acar, S., Ulu, E., Ozturk, H. (2017). Thermoeconomic method for determination of optimum insulation thickness of external walls for the houses: Case study for Turkey. *Journal of Sustainable Energy Technologies and Assessments*, 22, 1-8. <https://doi.org/10.1016/j.seta.2017.05.005>
- European Parliament, Commission delegated regulation (EU) (2010) 2010/31/EU of the European Parliament and of the council on the energy performance of buildings.
- Loukaidou, K., Michopoulos, A., Zachariadis, Th. (2017). Nearly-Zero Energy Buildings: Cost-Optimal Analysis of Building Envelope Characteristics. *Procedia Environmental Sciences*, 38, 20 – 27. <https://doi.org/10.1016/j.proenv.2017.03.069>
- United Nations Environment Programme (2009), Building and Climate Change. Summary for Decision Makers. (Date of Access 2018, June 28) Retrieved from http://www.greeningtheblue.org/sites/default/files/Buildings%20and%20climate%20change_0.pdf
- Енерго Про (2018). Действащи цени на електроенергията, www.energo-pro.bg (Energo Pro (2018). Actual prices of electrical energy (Date of Access 2018, June 30) Retrieved from <https://www.energo-pro.bg>).
- Досева, Н., Чакърова, Д. (2017) Оптимална дебелина на изолацията на външни ограждащи елементи на жилищна сграда за условията на България. XXII Научна конференция с международно участие, ЕМФ 2017, стр. 223-229 (Doseva, N., Chakyrova, D. (2017) Optimizing thermal insulation thickness of the residential buildings external walls for Bulgarian's climate and market conditions)
- Министерство на регионалното развитие и благоустройство (2017). Наредба №7 от 15.12.2004 за енергийна ефективност на сгради. Изм. и доп. бр.93 на "Държавен вестник" (Ministry of Regional Development and Public Works (2017). Regulation №7 for energy efficiency in buildings).
- Министерство на регионалното развитие и благоустройството, Министерство на енергетиката (2016). Наредба № 15 от 28 юли 2005 г. за технически правила и нормативи за проектиране, изграждане и експлоатация на обектите и съоръженията за производство, пренос и разпределение на топлинна енергия. Изм. и доп. бр.6 на "Държавен вестник", (Ministry of Regional Development and Public Works (2016). Regulation №15 for technical rules and norms for the design, construction and operation of the units and equipment for the generation, transmission and distribution of heat)